IAF-99-B.2.05

THE GRACE MISSION: MEETING THE TECHNICAL CHALLENGES

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ABSTRACT

The Gravity Recovery and Climate Experiment (GRACE) mission is scheduled for launch in June 2001. Within the first year of the mission, the project has a minimum science requirement to deliver a new model of the Earth's static geoid with an error of less than 1 cm to spherical harmonic degree 70. However, the GRACE mission is designed to exceed this requirement by a factor of 25 or more. For spherical harmonic degrees of up to 40, we expect to improve the current knowledge of the gravity field by 1000 times.

The GRACE mission uses the satellite-to-satellite tracking (SST) technique. The twin GRACE satellites are the instruments that measure the nonuniformities in the Earth's gravity field. Nonuniformities in the gravity field cause the relative distance between the centers of mass of the two satellites to vary as they fly over the Earth. Atmospheric drag is the largest nongravitational disturbing force. Drag is measured and will be used to correct changes in the satellite-to-satellite range measured by an SST microwave link. The microwave link will measure changes in the range between the two GRACE satellites with an error approaching 1 μm. We discuss how these instrumentation requirements affect the configuration, the mass balance, the thermal control, and the aerodynamic design of the satellites, the microwave SST link, and the accelerometer. Finally, the question of how noise in these components limits the overall accuracy of the gravity models is addressed.

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INTRODUCTION

Historical Perspective

Following a long line of proposed missions—Gravity Research Mission (1985), ARISTOTELES (1990), and GAMES (1994), to name a few[1]—GRACE is the first high-resolution gravity mission to be approved for implementation. Selected as one of the first two missions to be conducted under NASA's Earth System Science Pathfinder Program, GRACE is being implemented as a collaboration between NASA and the Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR).

Science Objectives and Payoff

Within the first year of the GRACE mission, the project has a minimum science requirement to deliver a new model of the Earth's static geoid with an error of less than 1 cm at a spatial resolution [(wavelength, λ)/2] of 300 km. This new model of the Earth's gravity field will enable a dramatic improvement in the utility of data from past, current, and future altimetry missions to measure ocean surface currents and the transport of heat from the equatorial to the polar regions of the Earth.

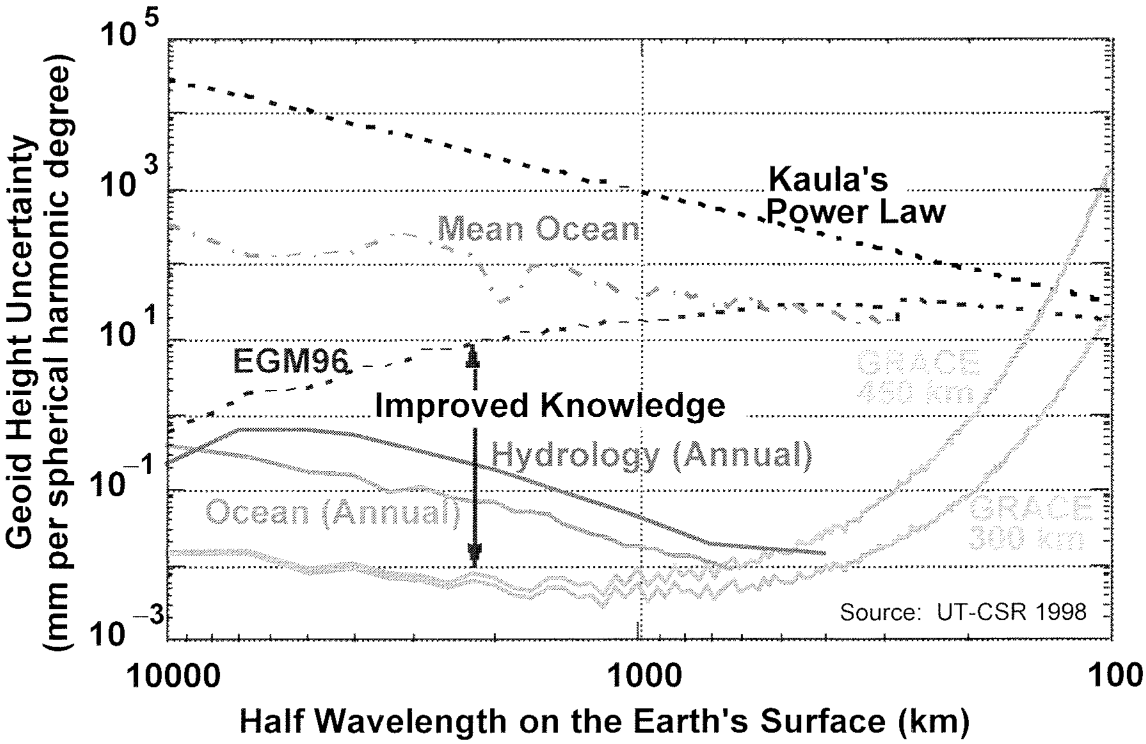

Figure 1. Global Spectra of Geophysical Signals and GRACE Accuracy

Moreover, the project fully expects the GRACE mission to exceed this minimum science requirement by more than a factor of 25. For spherical harmonic degrees up to 40, we expect to improve the current knowledge of the gravity field by 1000 times (see Figure 1), thereby reducing the contribution of gravity-field mismodeling to satellite radial orbit error to less than 1 mm for virtually all Earth-orbiting satellites, past, present, and future.

Because of the extreme sensitivity of 30-day gravity field solutions (geoid errors as low as 10 µm per degree) to larger-scale features (500 to 2000 km), the project expects the GRACE mission to be able to provide the data to facilitate an unprecedented study of time-variable gravity fields on a global scale. GRACE measurements will enable scientists to:

- Measure changes in the Greenland or portions of Antarctic ice sheets to less than 1 mm/year. This uncertainty corresponds to a contribution to global sea-level rise of less than 0.05 mm/yr.
- Measure changes in large aquifers (e. g., the Ogallalla aquifer in Nebraska) to 1 to 2 mm/yr water equivalent (1% to 2% of estimated Ogallalla depletion rate).
- Isolate geoid changes due to changes in global-sea-level to better than 0.1 mm/yr. In conjunction with altimetry, this allows us to separate the effect of changes in volume from changes in the mass of water in the oceans.

To study these time-varying gravity signatures, the GRACE data must be corrected for the time-varying signatures of the atmosphere, tides, and postglacial rebound. Making these corrections to the required accuracy represents a challenge to the science community.[2] However, these corrections are not relevant when GRACE data is used to measure changes in the global distribution of ocean-bottom pressure.[3]

From the gradients in ocean-bottom pressure GRACE gravity-field data will enable oceanographers to estimate deep ocean currents to better than 1 mm/s at a few hundred meters above the ocean floor.

Mission Description

The Gravity Recovery and Climate Experiment (GRACE) mission uses twin satellites, scheduled for launch on 23 June 2001. A near-polar orbit is planned with inclination between 87 and 89 degrees. The initial altitude will be in the range of 450 to 500 km. Aerodynamic drag on the satellites causes the altitude of the orbits to decay continually. When the altitude decays to approximately 300 km, the rate of decay approaches 1 km/day and the mission is essentially over. Since the rate of decay is strongly dependent on solar activity, some orbit management will be needed to achieve a lifetime of approximately five years. The ground track of the orbit is not controlled. This means that longitudinal sampling of the Earth's gravity field will vary throughout the mission. Except near 400 km in altitude, where the orbit has a two-day repeat cycle, adequate longitudinal sampling is achieved in 30 days or less.

INSTRUMENTATION REQUIREMENTS

Twin Satellites are the Instrument

The two GRACE satellites form the instrument that measures the nonuniformities in the Earth's gravity field. Nonuniformities in the gravity field cause the relative distance between the centers of mass of the two satellites to vary as they fly over the Earth. Anything else that causes the center of mass of either satellite to change is a source of error in the measurement.

Atmospheric drag is the largest nongravitational disturbing force. An accelerometer will measure the drag effect to better than one ten-billionth of the acceleration of gravity. The measured acceleration will be used to correct measured changes in the satellite-to-satellite range for drag, solar radiation pressure, attitude control thruster forces, etc. A satellite-to-satellite microwave link will measure changes in the range between the two GRACE spacecraft with an accuracy approaching 1 μm.

Calibrations and Alignments

The center of mass of each satellite must be collocated with the center of mass of the accelerometer's proof mass to within 100 μm. This is achieved by means of a center-of-mass trim system composed of six motor-driven masses—a redundant pair in each of the three axes of the satellites. The trim system has a resolution of 20 μm, and the on-orbit calibration technique has similar resolution.

The alignment of the K-band boresight with the star camera will also be measured on orbit, using a nodding maneuver and correlation between satellite attitude and range measurements on the microwave link. This will be done with an accuracy of better than 0.3 mrad.

Knowledge of the alignment of star camera axes to accelerometer axes is important for projecting the measurements on the nongravitational forces onto the satellite-to-satellite range measurement. This must be done to within 300 μrad, with a goal of 100 μrad. This is the only critical alignment that cannot be refined on orbit. Great care is being given to this measurement on the ground.

INSTRUMENTATION DESIGN FEATURES

Microwave Link

The GRACE instrument system is shown in Figure 2. Two instruments provide all the observables necessary for GRACE science. The Super STAR accelerometer (ACC) measures nongravitational accelerations of the spacecraft. The instrument processor unit (IPU) digitizes and determines metric observables from three GPS antennas and the K-band ranging assembly (KBR), as well as determining the spacecraft attitude from star camera images.

K-Band Ranging System

To achieve 1-μm precision, a laser system is usually the first candidate. While implementing the GRACE dual one-way range systems with lasers is straightforward, the range signals due to geoid variation are in a very low frequency range, below 0.05 Hz. In 1996, the technology to stabilize a laser's frequency at these long time scales had not been demonstrated. On the other hand, ultrastable oscillators (USOs) suitable for the GRACE mission were well developed and space qualified. Because the microwave wavelength is much longer than a laser wavelength, the phase of the signal must be stabilized to one part in 10,000. This technology is also available and qualified for space. To minimize the cost of the mission, a microwave system was selected to perform the ranging measurements.

The GRACE ranging system measures changes in distance between the GRACE satellites by exchanging linearly polarized K- and Ka-band carrier signals between the satellites. The transmissions of the satellites differ in frequency by 20 ppm and propagate with perpendicular polarization directions. At each spacecraft the transmit and receive signals are mixed to produce a quadrature baseband signal. The average of the phase change measured by each satellite results in a biased range for which clock noise is reduced by a high-pass filter with a 1-kHz cutoff frequency. Because the gravitational signal of interest lies below 0.05 Hz, this results in a tremendous improvement as

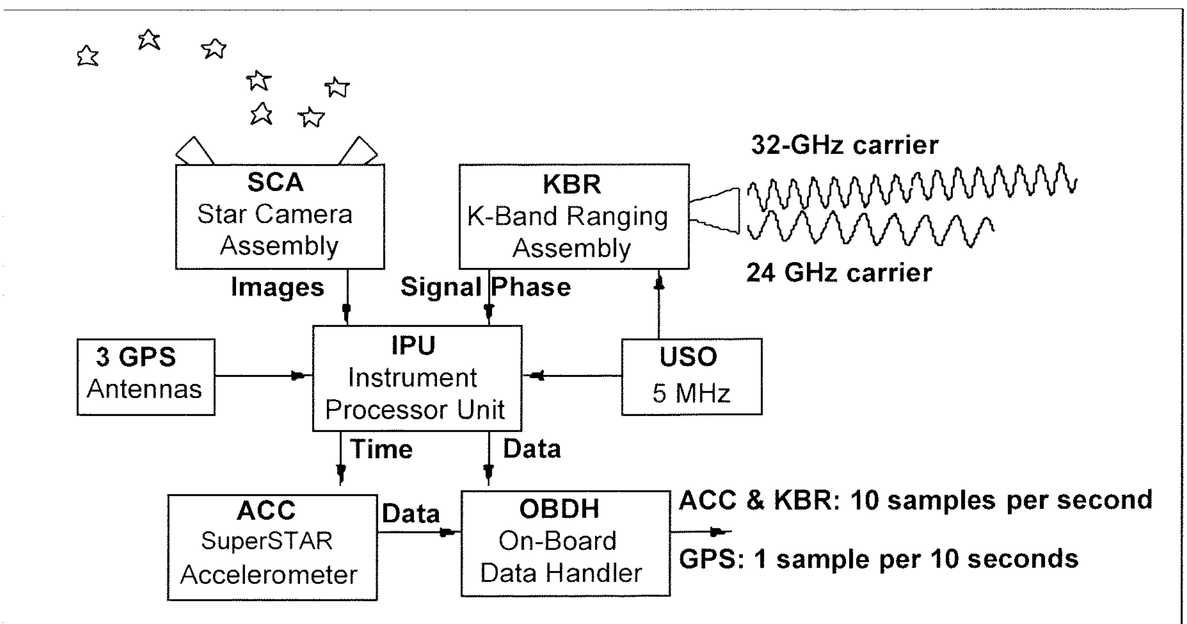

Figure 2. Overall Instrumentation Schematic Diagram

compared to a one-way phase measurement. The use of simple digital filters results in a reduction of 3×10^{-5}.[4]

The phase of the base-band signal is extracted digitally by the IPU. Transmit power and antenna aperture have been selected to produce a carrier-to-noise ratio (C/N0) and resulting one-sigma carrier phase precision as shown in Table 1. Two frequencies are used in order to reduce the error introduced by the ionosphere to a negligible amount. The ionosphere-free combination results in a phase precision worse than the components, as shown in the third line of Table 1.

Table 1. Precision Performance Figures

Band	Frequency (GHz)	Wavelength (μm)	Precision (μm)
K	24.5	12,240	0.59
Ka	32.7	9,179	0.79
Ionosphere-Free Precision			1.56
Dual One-Way Precision			1.10

The major error source affecting the range observable is the variation of the measured phase with the change in temperature of the components. This has been addressed by controlling the temperature of the KBR to 0.2 K, minimizing the length of waveguide runs, and selecting components with small thermal coefficients. In the unlikely event that the thermal control of the satellite is worse than 0.2 K, temperature measurements will allow the range to be corrected to about 10%.

Another error source is multipath. If the geometry between the transmitter and receiver change, multipath will introduce a variable range offset which is difficult to calibrate. This error source has been dealt with by measuring the multipath using a representative antenna and spacecraft front panel and setting spacecraft pointing requirements to keep the variable multipath error negligible.

Accelerometer

The GRACE accelerometer is derived from the ASTRE and STAR accelerometers that have been developed by the Office National d'Études et de Recherches Aérospatiales (ONERA) for the European Space Agency (ESA) and for the French Space Agency CNES. While the configuration of the sensor head has been adapted to the GRACE environment, the operation and technology are identical.

The accelerometer works by electrostatically controlling the position of a proof mass between capacitor plates that are fixed to the spacecraft. While gravitation affects both the proof mass and the spacecraft, nongravitational forces affect only the spacecraft. In order to keep the proof mass centered, the voltages suspending it must be adjusted using a control loop. Thus, the suspension control voltage is a measure of the nongravitational forces on the spacecraft.

The STAR accelerometer, which is the French contribution to the German CHAMP mission, has a planned resolution of 10^{-9} ms^{-2} integrated over the frequency bandwidth of 2×10^{-4} Hz to 0.1 Hz. Its full-scale range is 10^{-3} ms^{-2}. The expected resolution is based on accepted error source analysis, and the sensor head geometry is based on results from the ASTRE model.

The GRACE model (Super STAR) benefits from this development. Because of the GRACE orbit and the low-vibration design of the spacecraft, the full-scale range has been reduced to 5×10^{-5} ms^{-2}. This, combined with 0.1-K thermal control, allows the sensor core capacitive gaps to be increased from 75 μm to 175 μm and the proof mass offset voltage to be reduced from 20 V to 10 V. This results in a smaller acceleration bias by a factor of 20, and more importantly, bias fluctuations are also reduced by a factor of 20. The combined effect of these changes is a resolution on the order of 10^{-10} ms^{-2}.

Star Camera and Accelerometer Mounting

As shown in Figure 3, two star camera assemblies and the accelerometer are held in close alignment by mounting them together on a toroidal ring that is attached to the main equipment panel of the satellite using a kinematic mount. The accelerometer is attached to this toroidal ring by another kinematic mount.

Star Camera

Because the phase center of the ranging antenna is not collocated with the spacecraft center of mass, range variations due to rotations of the spacecraft about its center of mass must be removed. The distance between the center of mass and the phase center is 1.4 m, so to keep this source of error below 1 μm, the attitude must be known to better than $(2 \times 10^{-6}/1.4)1/2 = 1.2$ mrad. This measurement will be made with a star camera, which is expected to deliver a single-axis accuracy better than 0.024 mrad.

A second use of the star camera is to provide pointing information to the attitude control system in order to maintain accurate pointing. Precise pointing is required for two reasons. First, if the spacecraft pointing varies, the multipath signal will vary as well, resulting in a range measurement error. Second, if the phase centers are not kept close to the line between the centers of mass, the geometric error due to attitude variations is much larger than given by the formula above. Both of these errors are managed by maintaining absolute pointing accuracy to better than 1 mrad, including orbit propagation error.

SATELLITE DESIGN FEATURES

Because in the GRACE mission the satellites themselves act as the "proof masses" through which the gravitational field is sensed, the satellite design is crucial to the distance between the centers of mass of the two satellites. Thus, the location of the centers of mass must be determinable relative to the instruments on the satellite. In addition, the accelerometer proof mass must be close to the center of mass to avoid confusing internal satellite forces with external, nongravitational forces.

Because of these considerations, the satellite must be carefully designed for mass stabil-

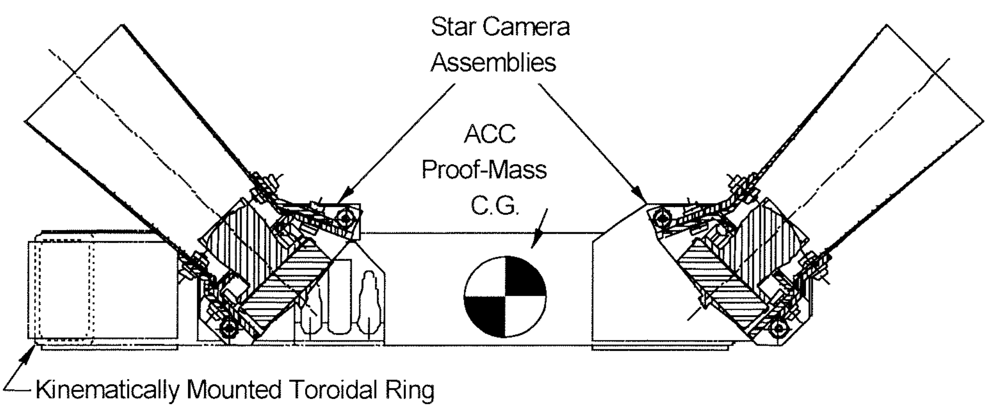

Figure 3. Star Camera and Accelerometer Mounting

ity, dimensional stability, and aerodynamic configuration.

Mass stability

The influence of mass balance

To minimize the consumption of cold gas for attitude control, the center of mass needs to be collocated (to an accuracy of 5 mm) with the center of action of the aerodynamic forces. But to minimize disturbances of the accelerometer, the center of mass also needs to be collocated (to an accuracy of 100 μm) with the center of mass of the proof mass of the accelerometer. This will be accomplished by first placing the equipment within the defined aerodynamic shape, then adding balance weights to get within 500 μm, and once in orbit, using a center-of-mass trim system to bring the collocation to within approximately 20 μm.

As shown in Figure 4, two tanks of pressurized nitrogen are symmetrically located about the center of mass of each satellite. The tanks are connected together so that internal pressure can be balanced. The line connecting the tanks has a solenoid valve which allows nitrogen to be used from only one tank at a time. In the science mode, nitrogen consumption is low enough to allow use from one tank for 6 months without violating center-of-gravity control requirements. This design prevents even small variations in tank temperature from shifting mass between the tanks in the frequency domain of interest.

With the exception of the small solenoid thruster valves, there are no moving parts on the satellite in the science mode. The body-fixed solar panels are rigid and insulated on the back side to prevent thermal warping.

Dimensional Stability

In order to connect the microwave phase measurements to motions of the center of mass, the distance between the ranging system phase centers and the center of mass must be stable to better than 3 μm at frequencies of twice per orbit. This is being done by building the satellite structure from low-coefficient-of-thermal-expansion (CTE) composite materials and by careful thermal design. An additional requirement is that the front panel of the spacecraft not move relative to the ranging system antenna, in order to minimize multipath variation.

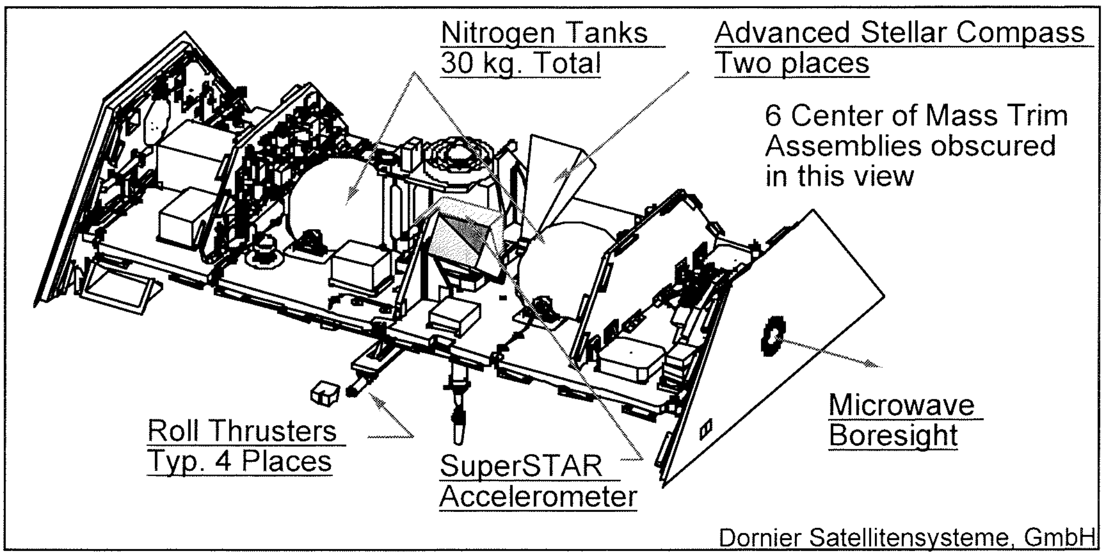

Figure 4. Satellite Internal Configuration

In order to transform the three-axis accelerometer results into the relevant coordinate system for science, the star camera pointing direction must be stable relative to the accelerometer to 0.8 mrad. This is accomplished by integrating the star cameras and accelerometers onto a single low-CTE fixture. The coupling between the star-camera/accelerometer frame and the science frame is determined by an on-orbit calibration.

Aerodynamic Configuration

The influence of aerodynamics

While the GRACE satellites are orbiting in space, they fly at a relatively low altitude: initially 450 to 500 km and then decaying to 300 km after five years. A high mass and low frontal area are needed by the GRACE satellites to cut through the atmosphere. Even so, because of the low altitude of the GRACE orbit, the atmospheric drag is approximately 1000 times greater than on a satellite like TOPEX/POSEIDON or JASON. Figure 5 shows two external views of the GRACE satellite.

Because the atmosphere rotates with the Earth, the apparent wind seen by the GRACE satellites shifts from left to right as the satellites orbit the Earth, with lateral wind speeds up to 10% of the orbital speed. The shape of the satellites is designed to keep the total aerodynamic force acting as close as possible through the center of mass of the satellite for the range of wind conditions to be encountered.

Quieting the Attitude Control Disturbances

Because the satellites are the instrument, it is necessary to minimize extraneous disturbances of the satellites. This means quieting the attitude control system. Accelerometer performance is degraded by random noise in the frequency domain of reaction wheels. Therefore reaction wheels are not used.

The GRACE attitude control system uses cold gas and magnetorquers. In the SST concept it is most important to quiet disturbances in the orbit plane. For this system this means an aerodynamically balanced satellite, small thrusters, and smart design choices. A set of four 10-mN thrusters is used for each axis. The yaw thrusters are naturally normal to the orbit plane. The roll thrusters are also oriented normal to the orbit plane, even though this reduces the level arm of these thrusters. Most of the thruster activity is in roll and yaw: 500,000 actuations over the life of the mission. The pitch thrusters must be in the orbit plane. However, the magnetorquers

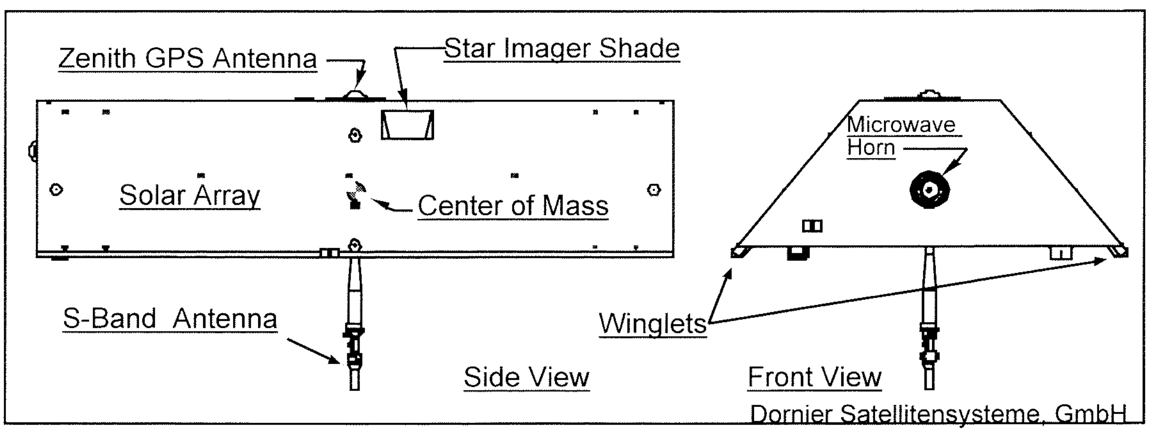

Figure 5. Exterior Views of Satellite

are almost completely effective in controlling the pitch attitude of the satellites: 2,000 actuations over the life of the mission

PERFORMANCE-LIMITING ERROR SOURCES

Noise Characteristics

In the SST system for gravity field measurement, there are three performance-limiting noise sources: (1) thermal noise from the ultrastable oscillator (USO), which manifests itself as phase noise on the transmitted signals and possibly as phase jitter on sampled microwave signals; (2) microwave system noise, which stems from thermal noise in the receivers on each end of the link; and (3) noise on the accelerometer signals, arising from many individual sources within the instrument. Each of these noise sources has a quite different spectrum in the frequency domain of interest to the GRACE mission.

Figure 6 shows the three sources mapped into a common parameter, namely the range acceleration observable. In this mapping the white microwave system noise increases with frequency and the 1/f noise of the USO is flat at low frequencies. Referring to Figure 6, it is important to note that we have designed the GRACE instrumentation system to roughly balance the contributions of the limiting noise sources to the error budget.

The accelerometer noise dominates the error budget at low frequencies, and the microwave system noise dominates the error at the high frequencies. The contribution of the noise of the USO at low frequency will depend on the ability to use the GPS to determine the ultralow-frequency behavior of the USO. For the estimates of the overall performance of GRACE indicated in Figure 1, the conservative assumption was used. It should not make any difference because the accelerometer noise dominates the errors at low frequencies.

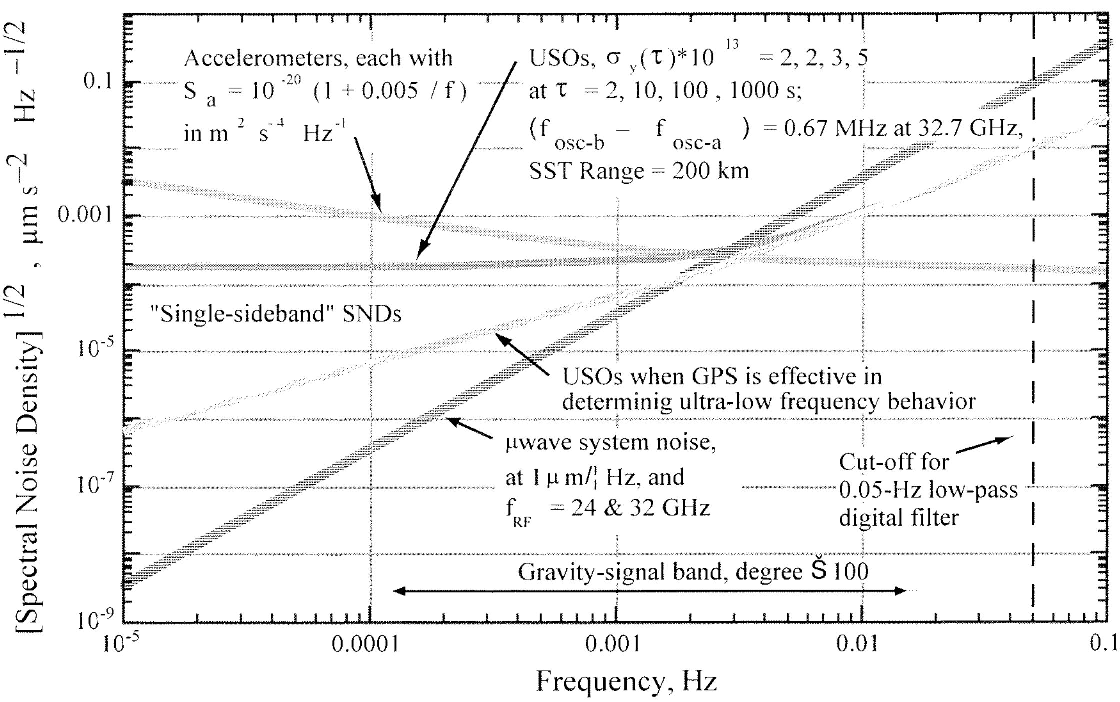

Figure 6. Spectral Noise Densities for Three Noise Sources for the Acceleration Observable

Mapping to the Gravity Coefficients

Because the partial derivative of each coefficient in the Legendre polynomial describing the shape of the Earth's geoid is a function of degree and order, the individual spectral noise density sources map into errors in the geoid in a spectrally distributed manner. A mapping of the three limiting error sources is shown in Figure 7. Since the acceleration observable is shown and perfect knowledge of the orbit was assumed, this mapping is only of theoretical interest. The results in Figure 1 are based on use of the range-rate observable and include the errors in solving for the orbits with GPS.

Systematic Measurement Errors

Of course, the random noise is only part of the story. The error in the models of the Earth's geoid will be affected by systematic measurement errors on the observables and by aliasing on high-frequency variations in the geoid (e.g., from errors in the tide models and in global atmospheric pressure distribution) into the solutions for the low-degree and low-order terms. The GRACE engineering team is controlling the systematic measurement errors to be less than the limiting noise errors at all wavelengths, the greatest challenge being at twice per orbit. Using GRACE data to its full potential is a challenge to the GRACE science team and the international science community.

SUMMARY AND CONCLUSIONS

- The SST concept for measuring the Earth's gravity field is particularly sensitive to the low degree and order (spherical harmonics < 50). The performance of the SST instrumentation concept as being implemented by GRACE is remarkably good at shorter wavelengths. Even at an altitude of 460 km (i.e., early in the mission), GRACE data has the potential to enable a 40× improvement in the accuracy of the geoid model to degree 100. Late in the mission (at 300 km altitude) the 40× improvement extends to degree 135.
- The design of the flight segment of the GRACE mission has been driven by the desire to open up new fields of research in the time-varying gravity fields that

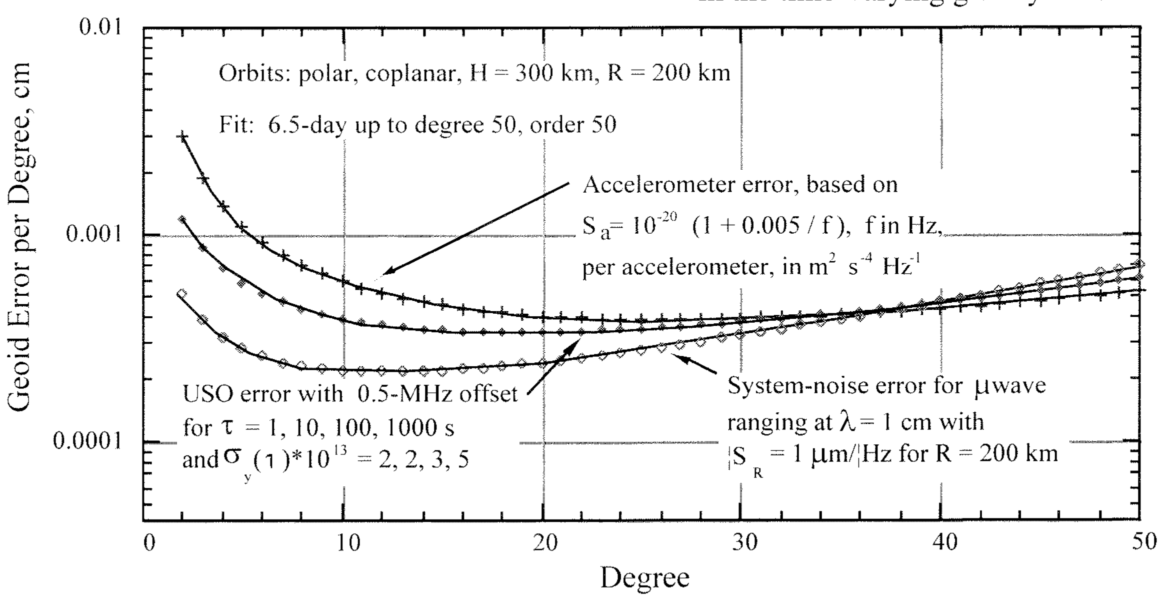

Figure 7. Gravity Coefficient Errors from a Hypothetical Fit to the Corrected Acceleration Observable

have the strongest signals in this spatial domain.

- The detailed design of the flight segment of the GRACE mission has confirmed and improved on our early expectations for performance.
- The gravity recovery performance is ultimately limited by noise on the microwave link, the USO, and the accelerometer. The GRACE instrumentation system design has balanced these noise sources so that no one source is dominant for all wavelength components of the resulting field.

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Earth Observation Symposium (i.e. Symposium B)
IAF-99-B.2.05

The GRACE Mission: Meeting the Technical Challenges

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50th International Astronautical Congress,
October 4-8,1999

- Mission Objectives and Payoff
- Expected Performance
- Mission Description
- Instrumentation Architecture and Performance
- Design of the Twin Satellites
- Limiting Errors
- Summary

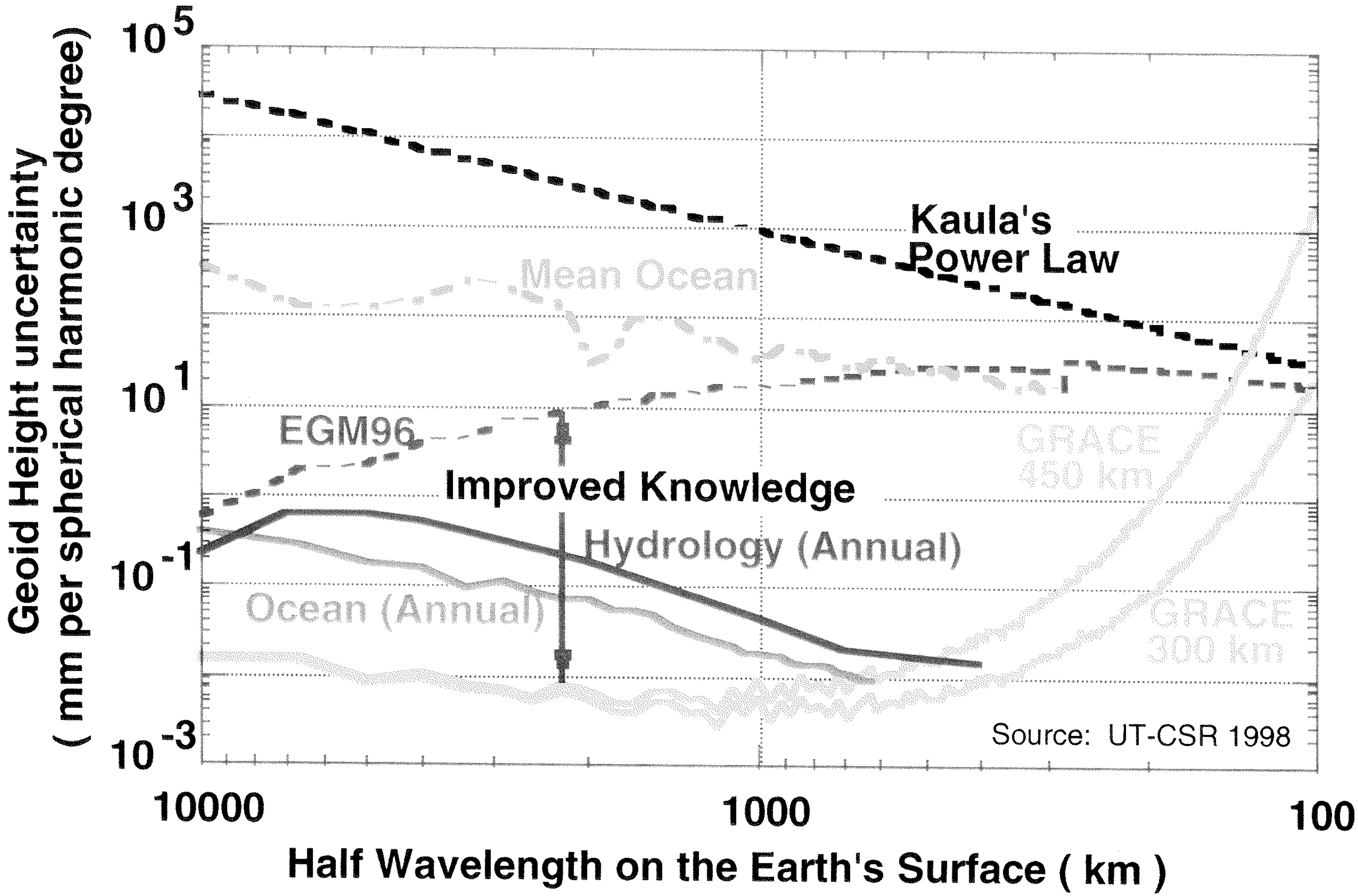
GRACE Mission: Objectives

- **Minimum Science Mission**
  - Cumulative Geoid Height RMS. < 1 cm for $n = 70$
    - i.e. 10,000 microns for spatial scales of 285 km.
  - Improves knowledge by a factor of eighteen (18).
  - Gravity field solution to $n \approx 100$
  - Accomplished with a mission life of < one year.

- **Expected Performance**
  - Cumulative Geoid Height - RMS. <350 microns for $n = 70$
  - Produce a new gravity field model every 30 days for five (5) years.

- **Payoff**
  - Improves knowledge by a factor of 1000 up to $n = 40$
  - Opens up completely new fields of climate research related to time-varying gravity fields

GRACE Mission: Expected Performance



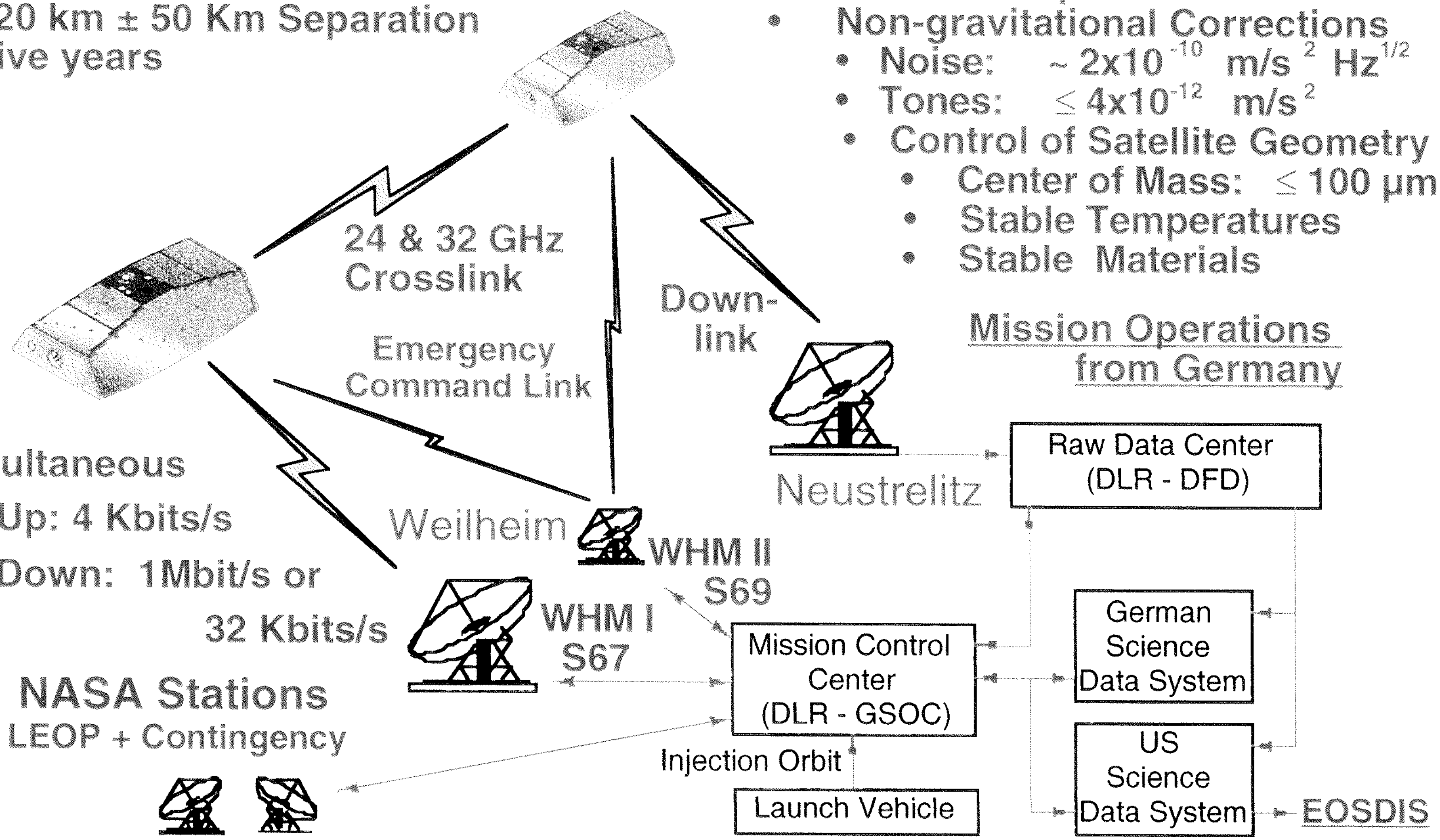
GRACE Mission Description

Launched from Plesetsks
Two 425 kg Satellites
Near Polar Orbits:

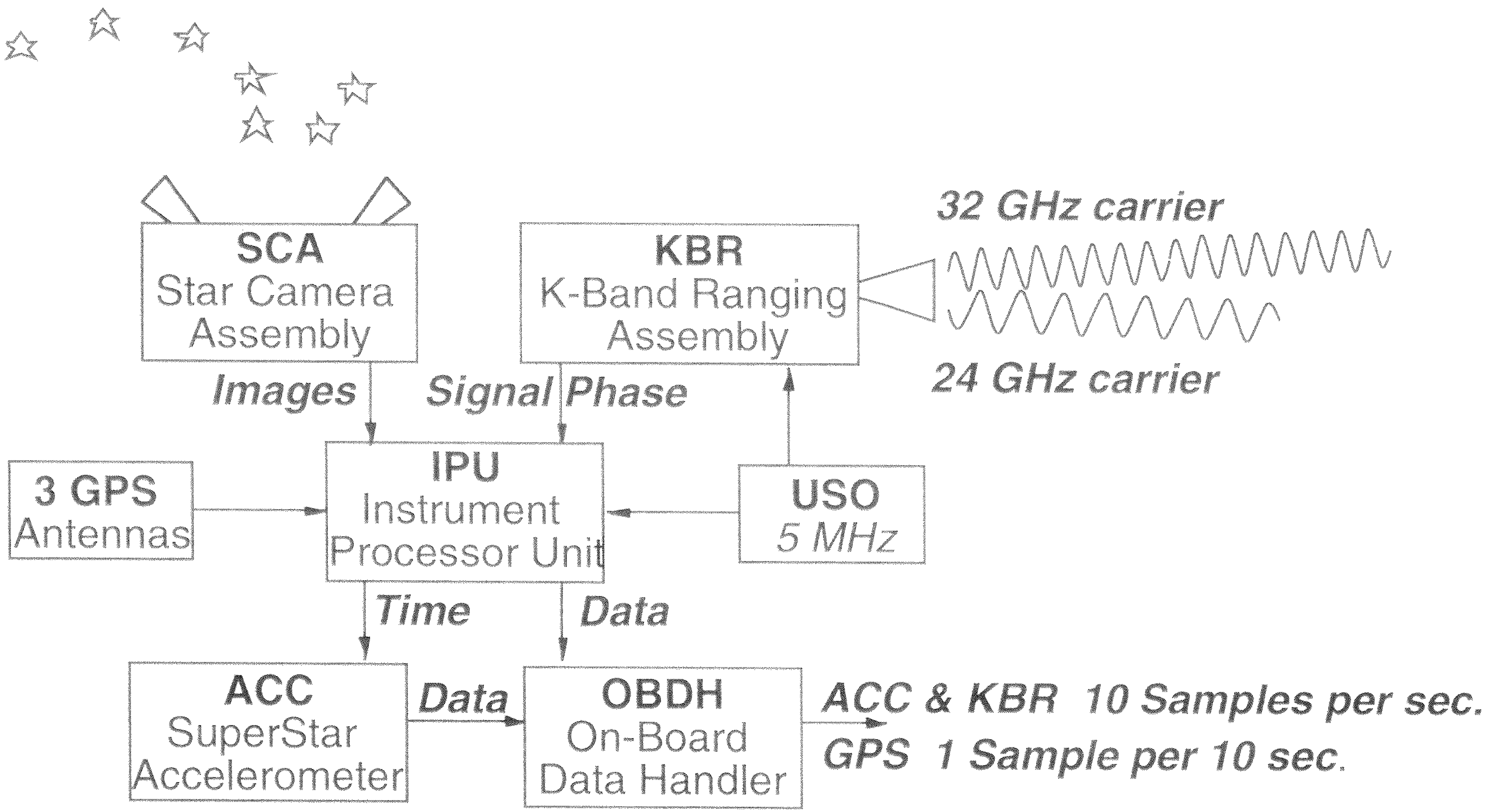
- Decays from 450 to 300 km Alt.
- 220 km ± 50 Km Separation
- Five years

The Twin Satellites are the Instrument

- Inter-satellite Range Measurement
  - Tones: $\leq 4 \mu m$ @ $\geq$ twice /orbit
  - Noise: $\leq 1 \mu m/Hz^{1/2}$
  - Non-gravitational Corrections
    - Noise: $\sim 2x10^{-10}$ m/s^2 $Hz^{1/2}$
    - Tones: $\leq 4x10^{-12}$ m/s^2
  - Control of Satellite Geometry
    - Center of Mass: ≤ 100 μm
    - Stable Temperatures
    - Stable Materials



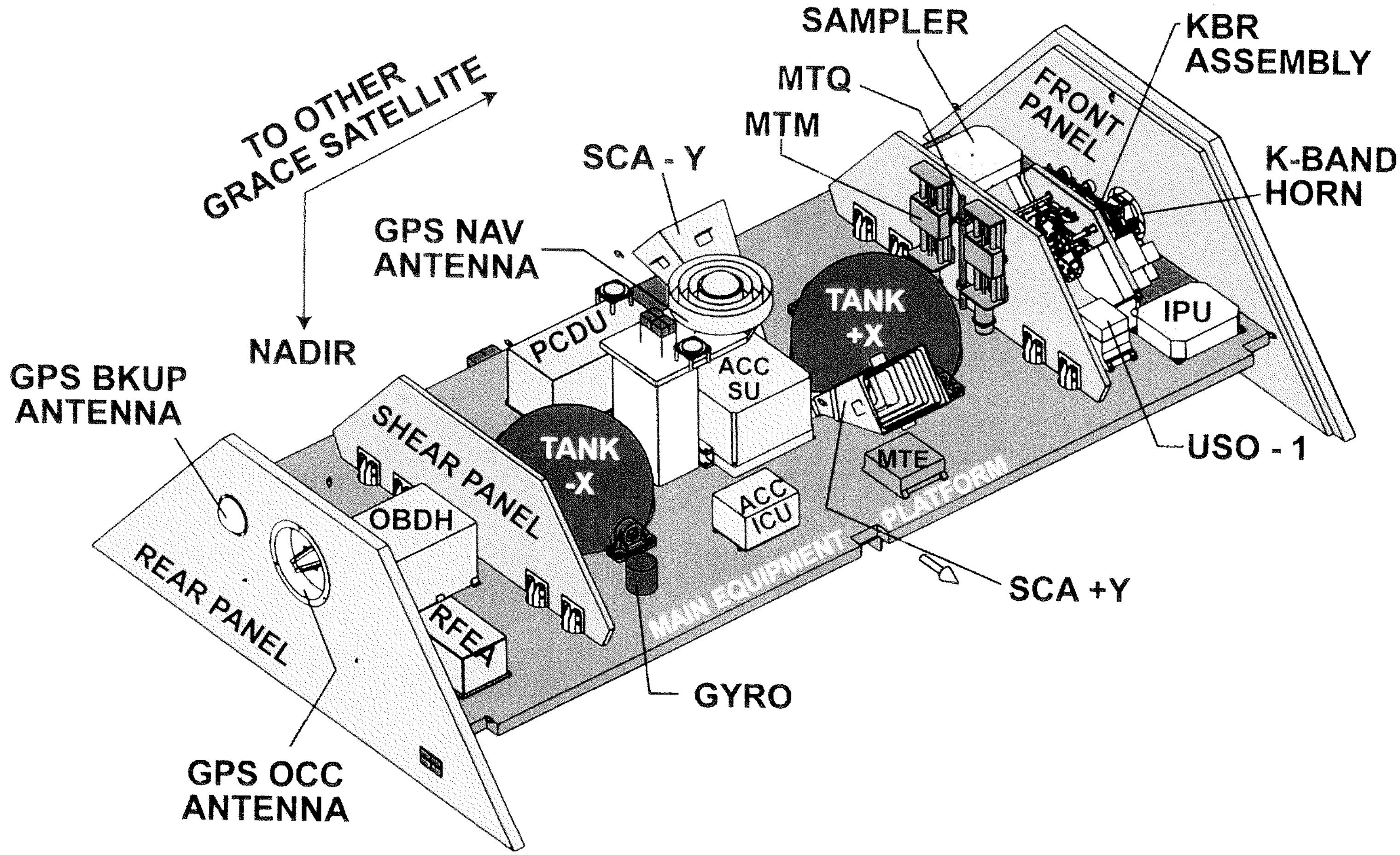
GRACE Mission: Instrumentation



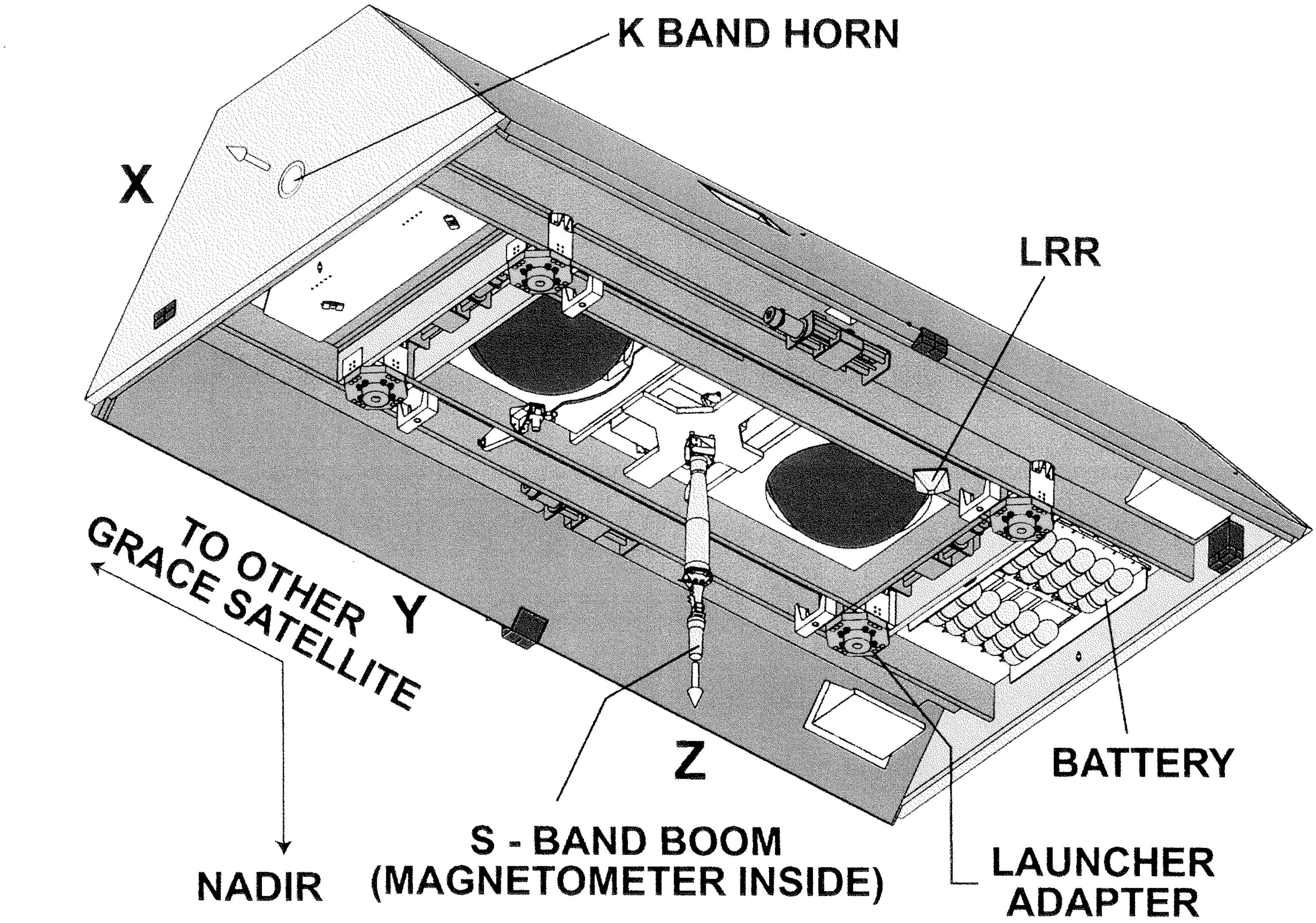
GRACE Mission: Microwave Link Precision

RF Band	Frequency (GHz)	Wavelength (µm)	Precision (µm)
K	24.5	12,240	0.59
Ka	32.7	9,179	0.79
Ionosphere-Free Precision			1.56
Dual-One-Way Precision			1.10

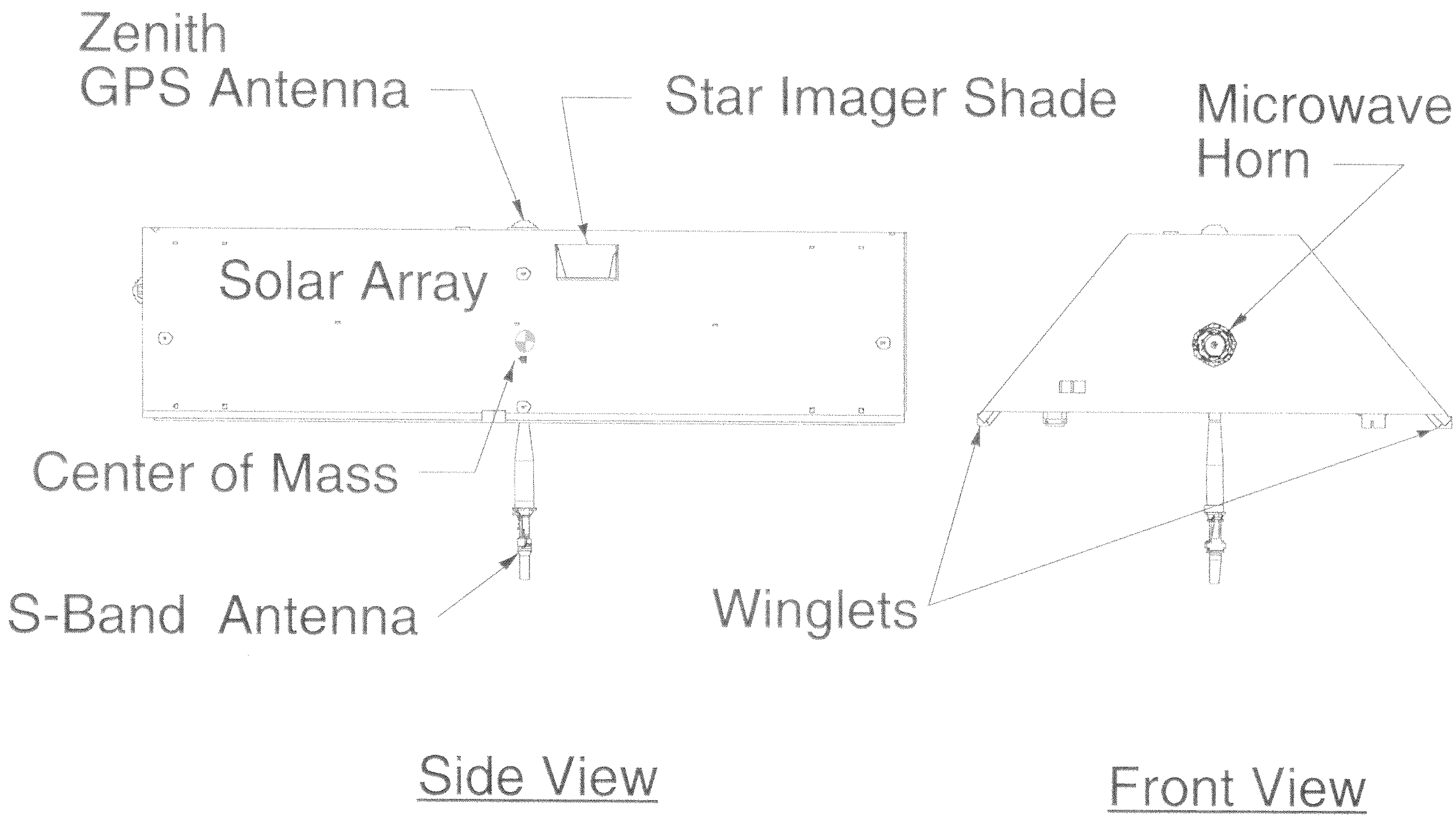
GRACE Mission: Satellite Design



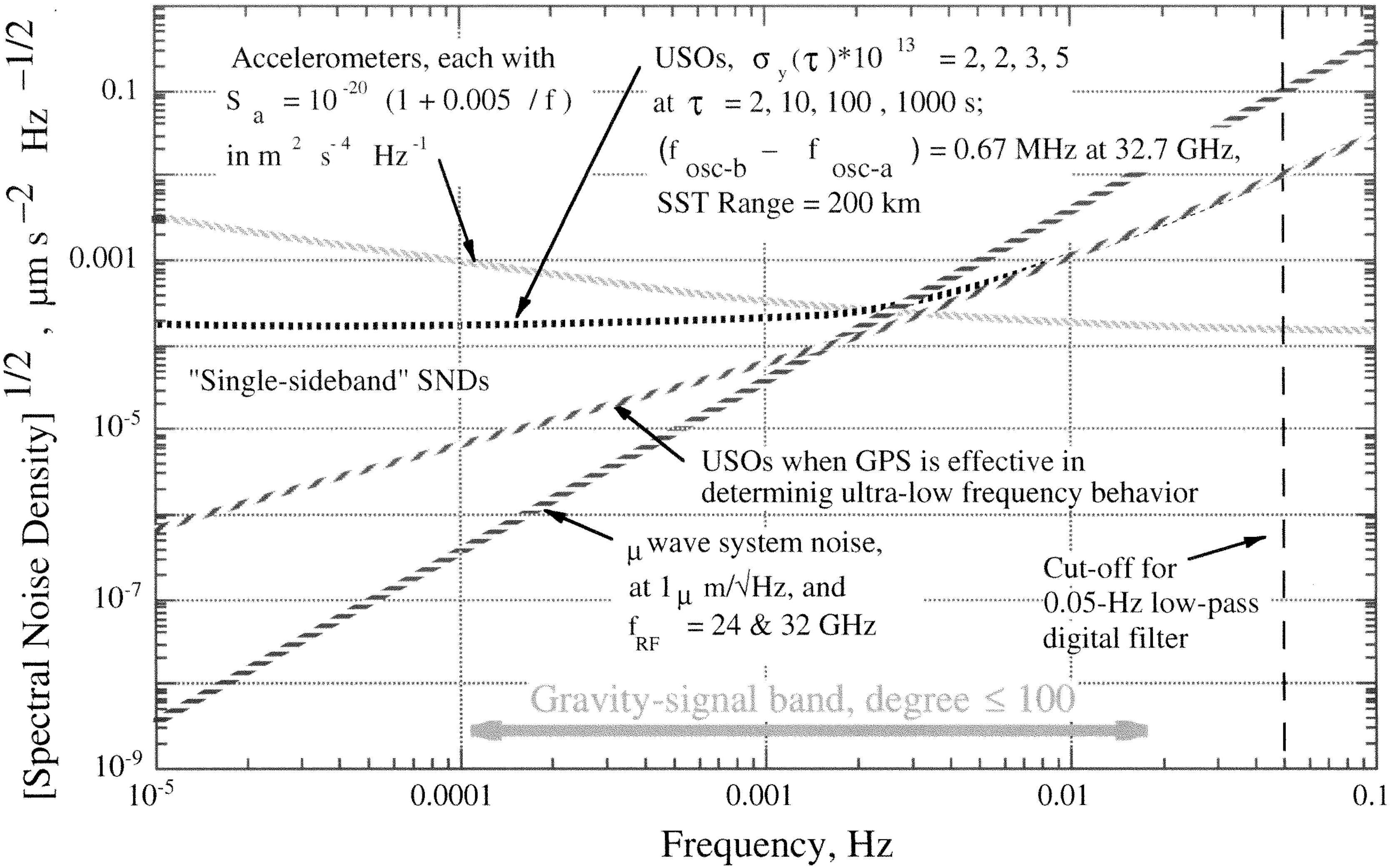
GRACE Mission: Satellite Design



GRACE Mission: Aerodynamics



Dornier Satellitensysteme, GmbH


Accelerometers, each with
S a = 10 -20 (1 + 0.005 / f)
in m 2 s -4 Hz -1
USOs, σ y (τ)*10 13 = 2, 2, 3, 5
at τ = 2, 10, 100 , 1000 s;
(f osc-b – f osc-a) = 0.67 MHz at 32.7 GHz,
SST Range = 200 km
"Single-sideband" SNDs
USOs when GPS is effective in
determinig ultra-low frequency behavior
μ wave system noise,
at 1 μ m/√Hz, and
f RF = 24 & 32 GHz
Cut-off for
0.05-Hz low-pass
digital filter
Gravity-signal band, degree ≤ 100
[Spectral Noise Density] 1/2 , μm s −2 Hz −1/2
0.1
0.001
10-5
10-7
10-9
10-5
0.0001
0.001
0.01
0.1
Frequency, Hz

GRACE Mission: Summary

- Improved on our early expectations for performance.
- Overall instrumentation noise has been used to set the requirements for controlling all of the systematic errors.
- Remarkably good at longer wavelengths - 1000x better
- Good at shorter wavelengths
  - Early in the mission, expect a 40× improvement in the accuracy of the geoid model to degree 100.
  - Late in the mission, expect to the 40× improvement extends to degree 135.
- Opens up new fields of research in the time-varying gravity fields

Be prepared
for a remarkable new data set

Today is 20 months and 18 days from launch.